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Linking Range Health Assessment Methodology with Science: Rough Fescue Grasslands of British Columbia

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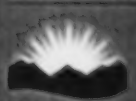

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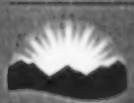

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Linking Range Health Assessment Methodology with Science Rough Fescue Grasslands of British Columbia

Reg Newman, Maja Krzic, and Brian Wallace

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Prepared by
Reg Newman
Research Range Ecologist
B.C. Ministry of Forests and Range
Kamloops, BC V2C 2T3

Maja Krzic
Program Director, Applied Biology;
Associate Professor, Applied Biology/Forest Sciences University of B.C.
Vancouver, BC V6T 1Z4

Brian Wallace
Range Ecologist, Soils
B.C. Ministry of Forests and Range
Kamloops, BC V2C 2T3

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ABSTRACT

Two range health assessment methods were tested against quantitative field measures of soil and vegetation in rough fescue grasslands: the British Columbia Ministry of Forests and Range Uplands Function Checklist (UFC) and the Grassland Monitoring Manual (GMM) produced by the Grasslands Conservation Council of British Columbia. The range health assessment scores were related to most of the quantitative measures taken. Only saturated hydraulic conductivity (K_s), colour and thickness of the soil A_h horizon, microbiotic crust, and bunchgrass seed heads were found to be completely unrelated. Both methods were found to be equally repeatable by samplers and were correlated to most selected quantitative measures of range health. The methods did not agree completely in their assessments of range health of the 28 treatment units examined. A better agreement between the two methods was achieved in range health scoring of poor sites but the methods did not agree in the scoring of better sites, especially those with a high component of Kentucky bluegrass. This is due to a different emphasis on degree of soil and site stability by the UFC method versus an emphasis on biotic integrity by the GMM method. There were potential weaknesses identified for both methods. The GMM method appears to be too heavily weighted towards plant community information, while the UFC method may benefit from increased plant community information, especially when applied to rough fescue–dominated grasslands.

PREFACE

This project was completed in 2006 using methodologies available at that time. This analysis does not consider changes that may have occurred subsequent to 2006.

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By the turn of the 19th century there was widespread grassland degradation from cattle overuse in the northwestern United States (Galbraith and Anderson 1971) and the southern interior of British Columbia (McLean 1982). It became clear that unregulated season-long grazing was leading to ecological damage and that the situation was detrimental to the ranching sector. Over the next century, it became understood that periods of drought coupled with intensive livestock use could severely restrict native perennial grasses, leading to colonization by unpalatable shrubs and early seral and exotic alien plant species.

The ecological status of rangelands has historically been assessed by a determination of "range condition," which is based on the difference between the existing plant community and the potential climax plant community for a specific range site (Clements 1920; Dyksterhuis 1949). A range site received a high range condition score if the existing plant community was similar to a benchmark climax plant community, and received progressively lower scores as it became more dissimilar. Today, a range site is commonly evaluated using a series of indicators that assess the health of the ecosystem.

The plant community approach to assessing ecological status came into question by rangeland scientists and managers in the 1990s (Pyke et al. 2002), sparking a re-evaluation of assessment methods. An expert panel from both the National Research Council and the Society for Range Management recommended a more holistic approach to determining the status of rangelands—one that incorporated an assessment of soil and plant processes in addition to plant community information. Commonly known as "range health," these assessments were proposed as replacements for traditional systems that were based on plant community seral stage of the site. A land unit would be evaluated by its ability to support a diversity of plant communities, each with different forage potentials and ability to protect against erosion.

Most range health assessment methods have been designed to be simpler than traditional methods of range condition assessment, allowing for wider use with minimal training (Pyke et al. 2002). Visual ratings of range health indicators are often favoured over quantitative measures. Because of the reliance on visual ratings, there are some concerns regarding the reliability and precision of range health assessments. The concept of range health monitoring has received numerous criticisms because of the use of qualitative assessments that do not necessarily correlate with quantitative measurements of vegetation and soil properties known to represent properly functioning ecosystems.

To define range health quantitatively, the three principal criteria for determination of range health outlined by the National Research Council (NRC) (1994) and Herrick et al. (2002) were used. The three principal criteria are: (1) degree of soil and site stability; (2) hydrologic function; and (3) biotic integrity. To address these criteria, various soil and vegetation properties were assessed or measured in this study (Table 1). The properties were selected because they can be obtained using sound, cost-effective monitoring techniques and/or because they assess key processes that are affected by grazing.

Two range health assessment methods are currently used or proposed to be used on British Columbia's rangelands and rough fescue (*Festuca*

campestris Rydb.) grasslands: (1) the British Columbia Ministry of Forests and Range Uplands Function Checklist assessment (B.C. Ministry of Forests 1997), and (2) the Grassland Monitoring Manual for British Columbia (Wikeem and Wikeem 2005).

The objective of this study was to determine the reliability of these two range health assessment methods by comparing their scores against quantitative measures of range health. A second objective was to examine the differences between the two methods.

TABLE 1 *Measured properties that incorporate soil and site stability, hydrologic function, and biotic integrity criteria*

Ecosystem property	Soil and site stability	Hydrologic function	Biotic integrity
Soil bulk density and soil mechanical resistance; indicators of soil compaction	×	×	
Aggregate stability; an indicator of soil stability and erosion resistance	×	×	×
Exposed mineral soil; an indicator of biomass production and erosion resistance	×	×	×
Saturated hydraulic conductivity; a measure of water infiltration rate	×	×	
Total soil carbon and nitrogen; measures of soil organic matter and soil nutrients	×	×	
Colour and thickness of soil Ah horizon; an indicator of soil organic matter content and history of erosion	×		×
Living above-ground biomass; a measure of site productivity		×	×
Dead above-ground biomass and cover (litter); an indicator of nutrient cycling		×	×
Microbiotic crust cover; an indicator of soil stability and nutrient cycling	×	×	×
Cover of existing native and alien invasive plant species; an indicator of seral state and recovery potential			×
Density and seed head count of rough fescue, Idaho fescue, and bluebunch wheatgrass; an indicator of reproductive capacity and plant recruitment potential		×	×
Species richness of the plant community; an indicator of plant community resilience			×

2 MATERIALS AND METHODS

2.1 Site Description

In total, 28 treatment units were selected from 10 grassland sites within the Thompson Nicola region of British Columbia (Table 2). All sites, except one, had established exclosures with historical vegetation monitoring data available. Exclosures maintained by the British Columbia Range Reference Areas program (B.C. Ministry of Forests and Range 2005) were used whenever possible. The period of livestock exclusion varied from 13 to 76 years. Sites selected were in open grassland with a potential natural plant community dominated by rough fescue. At least one corresponding grazed treatment unit was also available at each grassland site. The historical level of grazing is not reported here due to the lack of verifiable data. At five of the 10 sites, a third treatment unit was selected to provide representation of early plant community seral stages. As an intentional result of the selection process, the current plant communities varied widely among treatment units (Appendix 1). Soils were generally silty loam Dark Brown to Black Chernozems developed over morainal deposits.

2.2 Sampling and Assessment

Within each treatment unit, the basic layout consisted of five parallel transects each 30 m long, spaced 5 m apart. Pre-existing transects were incorporated into the sampling design whenever possible, resulting in modification of the basic layout. However, the total length of transect line sampled was always maintained at 150 m. Plant species composition was assessed along the transects, while soil sampling occurred midway between transects to avoid damaging plants used for long-term monitoring. Destructive sampling, such as clipping for above-ground biomass, occurred outside the long-term plant monitoring area but within 2 m of it. All sampling and assessment was conducted during June 2006 except for plant biomass, plant density, and seed head counts, which were completed in August 2006.

TABLE 2 *Selected characteristics of 28 grassland treatment units (T.U.s) in the Thompson Nicola region of British Columbia*

Area	Site name	T.U. code	Treatment	Elevation (m)	BEC unit[a]	Date established[b]	Slope (%) / aspect (°)
Kamloops	Lac du Bois fert. trial[c] 6	LF6G1	Grazed	940	IDFxh2a	1981	13 / 81
	Lac du Bois fert. trial 6	LF6G2	Grazed	940	IDFxh2a	1981	8 / 81
	Lac du Bois fert. trial 6	LF6U1	Ungrazed	940	IDFxh2a	1981	10 / 81
Kamloops	Lac du Bois fert. trial 1	LF1G1	Grazed	980	IDFxh2a	1981	5 / 107
	Lac du Bois fert. trial 1	LF1G2	Grazed	980	IDFxh2a	1981	5 / 107
	Lac du Bois fert. trial 1	LF1U1	Ungrazed	980	IDFxh2a	1981	5 / 107
Kamloops	Deep Lake fert. trial 1	DF1G1	Grazed	900	IDFxh2a	1981	15 / 90
	Deep Lake fert. trial 1	DF1G2	Grazed	900	IDFxh2a	1981	5 / 90
	Deep Lake fert. trial 1	DF1U1	Ungrazed	900	IDFxh2a	1981	15 / 90
Kamloops	Deep Lake fert. trial 3	DF3G1	Grazed	880	IDFxh2a	1981	20 / 90
	Deep Lake fert. trial 3	DF3G2	Grazed	880	IDFxh2a	1981	5 / 90
	Deep Lake fert. trial 3	DF3U1	Ungrazed	880	IDFxh2a	1981	15 / 90
Kamloops	Ag. Canada weather station[d]	AG1G1	Grazed	920	IDFxh2a	1975	5 / 270
	Ag. Canada weather station	AG1G2	Grazed	920	IDFxh2a	1975	2 / 270
	Ag. Canada weather station	AG1U1	Ungrazed	920	IDFxh2a	1975	7 / 270
Kamloops	Gaura field	GF1G1	Grazed	850	BGxw1	NA	5 / 270
	Gaura field	GF1G2	Grazed	850	BGxw1	NA	5 / 270
	Gaura field	GF1G3	Grazed	850	BGxw1	NA	10 / 270
Merritt	Microwave repeater	MR1G1	Grazed	1290	IDFxh2a	1975[e]	2 / 250
	Microwave repeater	MR1U1	Ungrazed	1290	IDFxh2a	1975[e]	2 / 250
Merritt	Goose Lake	GL1G1	Grazed	1170	IDFxh2a	1931	5 / 125
	Goose Lake	GL1U1	Ungrazed	1170	IDFxh2a	1931	5 / 125
Merritt	Drum Lake	DL1G1	Grazed	1060	IDFxh2a	1931	5 / 170
	Drum Lake	DL1U1	Ungrazed	1060	IDFxh2a	1931	5 / 170
	Drum Lake	DL1U2	Ungrazed	1060	IDFxh2a	1994	5 / 170
Merritt	Tunkwa Lake	TL1G1	Grazed	1170	IDFdk1	1963	5 / 25
	Tunkwa Lake	TL1U1	Ungrazed	1170	IDFdk1	1963	5 / 25
	Tunkwa Lake	TL1U2	Ungrazed	1170	IDFdk1	1993	4 / 25

a Biogeoclimatic ecosystem classification system (Lloyd et al. 1990)
b Date of establishment of the exclosures
c fert. trial = a fertilizer trial conducted in the Lac du Bois grasslands from 1985 to 1990
d Agriculture and Agri-Food Canada exclosure containing a meteorological station
e Estimated

2.2.1 Range health assessment methods

Two range health assessment methods were tested:

1. the B.C. Ministry of Forests and Range Uplands Function Checklist assessment method (B.C. Ministry of Forests 1997); and
2. the Grassland Monitoring Manual for rough fescue grasslands (Wikeem and Wikeem 2005).

These methods were chosen because they were either already in use during 2006 or were proposed to be used in British Columbia. Four individuals independently assessed the range health of each treatment unit. The assessments were conducted at the same location as the vegetation and soil transects, generally over an area of about 875 m^2. All individuals received the same level of range health assessment training; however, their field experience in range/plant ecology varied greatly. Two of the samplers had minimal field experience (~1 year), another had 6 years experience, while the fourth had 22 years experience. This variation of field experience somewhat reflects the variation expected among users of range health assessments methods.

Fourteen questions were evaluated for the B.C. Ministry of Forests and Range Uplands Function Checklist assessment method, hereafter referred to as the UFC method, while eight questions were evaluated for the Grassland Monitoring Manual of British Columbia method, hereafter referred to as the GMM method (Table 3). The sum of the scores for the questions for each treatment unit was calculated and expressed as a percentage of the maximum total score. This allowed comparison of the two methods.

TABLE 3 *Questions evaluated for two range health assessment methods used at 28 treatment units in the Thompson Nicola region of British Columbia*

	B.C. Ministry of Forests and Range Uplands Function Checklist assessment method (UFC)	Scoring
1	Organic material (plant litter, standing vegetation) protects soil surface from raindrop impact and evaporative effects of sun and wind.	yes / no
2	Water will easily infiltrate the soil surface (absence of physical soil crusting, capping).	yes / no
3	Subsurface soil conditions support infiltration (compaction layers are uncommon).	yes / no
4	Standing vegetation and plant litter detain overland water flow and trap sediment.	yes / no
5	Non-stream ephemeral drainages are stable (sufficient vegetation is present to protect against downcutting).	yes / no
6	The plant community is showing good vigour.	yes / no
7	There is recruitment of desirable plant species (new seedlings).	yes / no
8	The plant community reflects a fully occupied root zone.	yes / no
9	Seeps, springs, and ephemeral drainages support vigourous stands of phreatophytic plants.	yes / no
10	Biological breakdown of plant residues/organic material is apparent (decomposition as opposed to oxidization).	yes / no
11	Biological breakdown of livestock dung is rapid.	yes / no
12	A diversity of vertebrate and invertebrate life is evident.	yes / no
13	Evidence of rills, gullies, pedestalling, and other excessive soil movement is uncommon.	yes / no
14	There is little visual evidence of pedestalling of plants or rocks. Pedestals present are sloping or rounding and accumulating litter.	yes / no
	Maximum total score = 14 (yes = 1; no = 0)	
	Grassland Monitoring Manual for rough fescue grasslands (GMM)	**Scoring**
1	Plant community composition: Key bunchgrasses	40, 25, 10, 0
2	Plant community structure: Expected layers	10, 6, 2, 0
3a	Nutrient and hydrological cycling: Amount and distribution of litter	12, 15, 8, 0
3b	Nutrient and hydrological cycling: Litter cover	1, 5, 0
4a	Site stability: Erosion	9, 6, 3
4b	Site stability: Bare soil	6, 4, 2, 0
5a	Invasive plants: Canopy cover	5, 3, 1, 0
5b	Invasive plants: Distribution	5, 3, 1, 0
	Maximum total score = 88	

2.2.2 Soil properties

Total soil carbon and nitrogen Measures of soil total carbon and nitrogen represent the total inventory of soil organic matter, while soil organic matter is considered to be a key attribute of soil quality (Gregorich et al. 1994). Soil organic matter is involved in many soil chemical, biological, and physical processes. For example, soil organic matter influences soil compactability, friability, soil-water holding capacity, aggregation, water infiltration, nutrient supply, and susceptibility to erosion.

Soil samples for determination of total carbon and nitrogen were taken at 0–7.5 and 7.5–15 cm depths. Samples were air-dried and ground to pass through a 2.0-mm sieve. Total soil carbon (Nelson and Sommers 1996) and total nitrogen (McGill and Figueiredo 1993) were determined by dry combustion method using a LECO automated analyzer (Leco CHN-600 Elemental Analyzer). Four samples were taken at random locations along each soil sampling transect and were composited, resulting in five laboratory-analyzed samples at each depth per treatment unit.

Colour and thickness of soil A_h horizon The colour of the A_h horizon was rated according to the Munsell notation (Munsell Soil Color Charts 2000) on moist samples. Two samples were taken at random locations along each soil transect (totalling 10 samples per treatment unit). The thickness of the A_h horizon was measured to the nearest centimetre in the field. Two measurements were taken at random locations along each transect (10 measurements per treatment unit).

Soil aggregate stability Soil aggregate stability is often used to characterize soil susceptibility to erosion, crust formation, hard setting, and compaction (Angers and Mehuys 1993). Presence of stable aggregates leads to improved water infiltration by maintaining soil pores that allow water to percolate down into the soil profile, thereby reducing the risk of erosion from overland flow. When unstable aggregates are exposed to external stress (e.g., grazing, tillage), they easily break apart into small aggregates and primary mineral particles (i.e., clay, silt, sand) that then clog soil pores used for water drainage and air exchange through the soil profile.

Five samples for determination of soil aggregate stability were taken at 0–7.5 cm depth at random locations along each soil transect and were composited, resulting in five laboratory-analyzed samples per treatment unit. Aggregates that were 2–6 mm were tested for their stability following repeated submersion in water (Nimmo and Perkins 2002). Highly stable aggregates will have a high proportion of aggregates that remain in the 2–6 mm aggregate size class, whereas aggregates that are less stable will end up in the 1–2, 0.25–1, and < 0.25 mm size classes.

Soil bulk density Intact soil samples for bulk density determination (Blake and Hartge 1986) were taken with a drop-hammer sampler (with a core of 7.5 × 7.5 cm) at 0–7.5 cm depth. The samples were dried at 105°C for 48 hours in a forced-air oven. Coarse fragments (diameter > 2 mm) within the sample were screened out and weighed. The volume of mineral coarse fragments was determined from dry mass and was assumed to have a particle density of 2.65 Mg m^{-3}. Soil bulk density was calculated as the mass of dry, coarse fragment-free mineral soil per volume of field-moist soil, where volume was also calculated on a coarse fragment-free basis. Bulk density samples were taken at three random locations within each treatment unit (three samples per treatment unit).

Soil mechanical resistance Soil mechanical resistance is a measure of the force required to penetrate the soil. Soil mechanical resistance is considered to approximate the resistance encountered by plant roots growing in the soil. Compacted soils have higher mechanical resistance than uncompacted soils.

Soil mechanical resistance (Bradford 1986) of six soil profiles was recorded at random locations along each of the five transects (30 measurements per treatment unit) to a 15-cm soil depth. Measurements were recorded at depth intervals of 1.5 cm, using a hand-pushed 13-mm diameter cone (30°) penetrometer with data logger (Agridry Rimik PTY Ltd., Toowoomba, QLD, Australia). Soil mechanical resistance measures were not corrected for soil moisture content.

Saturated hydraulic conductivity Saturated hydraulic conductivity (K_s) (Zhang 1997) of the soil surface was measured using a mini-disk infiltrometer (Decagon Devices, Inc., Pullman, Wash). One measurement was recorded at a random location along each of the five transects (five measurements per treatment unit).

Exposed mineral soil The percentage of exposed mineral soil was assessed within 0.5 × 0.2 m quadrats. Ten assessments were completed at random locations along each of the five soil transects (50 assessments per treatment unit).

2.2.3 Vegetation properties

Cover of dominant and subdominant vascular and non-vascular plant species The cover of vascular plant species was assessed using a modified canopy coverage method (Daubenmire 1959). The cover of dominant, important subdominant, and alien invasive plant species was measured to the nearest percentage within 0.5 × 0.2-m quadrats. Vascular plant species were identified to genus, species, and subspecies using nomenclature provided by Douglas et al. (1998–2001). The percentage of ground surface covered by microbiotic crust (including lichens, algal crust, and bryophytes) was also assessed. The percentage of ground surface covered by lichens (identified to life form) was also determined separately. Ten assessments of vascular and non-vascular plant species were completed at random locations along each of the five transects (50 assessments per treatment unit).

Plant biomass Living above-ground biomass was estimated from peak annual standing crop of grasses and forbs. Areas of 0.5 m^2 were clipped to ground level, and the plant litter was separated from the current year's growth of forbs and grasses. Living plant material was sorted by species or category (Table 4), stored in paper bags, and air-dried to minimize decomposition. Standing litter was retained and combined with fallen litter (detached above-ground dead plant material not incorporated into mineral soil). All samples were oven-dried at 70°C to a constant weight and were weighed to the nearest 0.1 g. Five plots were randomly located within each treatment unit. Portable cages (1 × 1 × 1 m) were used on unfenced treatment units to exclude grazing by domestic and wild ungulates during May–August.

TABLE 4 *Categories used for separation of clipped plant biomass material at 28 treatment units in the Thompson Nicola region of British Columbia*

Clipping category	Plant species or description
Invasive alien plants	Spotted knapweed Dalmation toadflax
Rough fescue	
Bluebunch wheatgrass	
Litter	Standing and fallen litter
Mixed forbs	All non-invasive forbs
Mixed grasses	All grasses excluding those identified in other categories

Bunchgrass density and seed heads The density of three dominant or subdominant perennial bunchgrass species, rough fescue, bluebunch wheatgrass (*Pseudoroegneria spicata* (Pursh) A. Löve), and Idaho fescue (*Festuca idahoensis* Elmer) was determined within 1 m^2 plots. Five plots were randomly located within each treatment unit. Portable cages (1 × 1 × 1 m) were used on unfenced treatment units to exclude grazing by domestic and wild ungulates during May–August. Plants were categorized as large (> 4 cm diameter) or small (< 4 cm diameter) at the time of sampling. The number of seed heads produced by the three bunchgrass species was counted within 0.5-m^2 plots nested within the density plot.

Plant species richness Species richness is the number of plant species per specified collection area and is comparable to species density as defined by Magurran (1988). Species richness is one of the simplest indices of diversity. For this study, plant species richness was derived from plant species cover data. The specified collection area in this study was 5 m^2 (50 Daubenmire frames, each 0.1 m^2). It should be noted that the use of Daubenmire frames to determine species richness limits the ability to identify rare species.

2.3 Data Analysis

Simple linear regression was used to determine if individual quantitative variables (e.g., soil carbon, hydraulic conductivity, soil N) were related to total range health scores, expressed as a percentage of the maximum possible range health score. Treatment units were subsampled from three to 50 times, depending on the parameter measured, to provide a reliable estimate of the mean. Simple linear and second degree polynomial models were tested.

Backwards multiple linear regression was used to determine which quantitative variables had the strongest relationships to each range health score. An exit significance level of $P > 0.15$ was used during backwards selection. Simple and multiple regression was conducted using the SAS procedure REG (SAS 2003).

Principal components analysis (PCA) was used to identify patterns in the data based on the set of quantitative variables measured at each treatment unit. Range health scores were not included in the ordination. The SAS procedure PRINCOMP was used (SAS 2003).

The coefficient of variation (CV) was used to compare data series variation among different measures. The coefficient of variation measures the spread of a set of data as a proportion of its mean. A modified Bennett's test was used to determine if CVs were different among groups (Gupta and Ma 1996).

3.1 Direct Comparison of the Range Health Assessment Methods

3.1.1 Consistency of individuals carrying out the assessments The four individuals who did the assessments were relatively consistent in their evaluation of the questions for both assessment methods. The evaluation of range health using the GMM method varied in scoring among samplers by a CV of 15.1%. The same measure for the UFC method yielded a CV of 12.7%. Based on a modified Bennett's test, the CV among samplers was not significantly different ($P = 0.21$) between the GMM and UFC methods, indicating that both methods were equally repeatable.

Questions 5 and 9 of the UFC method (Table 3) were found to be not applicable to any of the treatment units, likely because they relate to drainages, which is intentionally not included in confined upland reference sites. Questions 10 and 11 of the UFC method were found to be difficult to assess reliably during a one-time inspection and were therefore rarely scored. Consequently, range health was usually assessed using only 10 of the 14 possible UFC questions. All GMM questions were found to be applicable in this study.

3.1.2 Discrimination power The range health scores varied among the treatment units to a greater extent for the GMM method than for the UFC method. This was reflected by the higher CV ($P = 0.03$) and the broader range of scores among treatment units (Table 5). Providing that the methods are equally sensitive to the measured property, a higher CV among scores for the treatment units may indicate a greater ability to discriminate among them. For example, if two obviously different treatment units were scored the same, this would result in a low CV, with no ability to separate the two treatment units. Based on this analysis, the GMM method found more differences among the treatment units than did the UFC method and therefore may have greater ability to discriminate among the treatment units.

TABLE 5 *Descriptive statistics for range health scores (expressed as a percentage of maximum possible score) averaged across the 28 treatment units in the Thompson Nicola region of British Columbia. GMM: Grassland Monitoring Manual; UFC: Uplands Function Checklist*

Statistic	GMM	UFC
Mean	61.91	80.96
Standard Error	4.61	3.74
Median	55.00	89.44
Mode	55.00	92.50
Standard Deviation	24.41	19.82
Coefficient of Variation (%)	39	24
Sample Variance	595.90	392.66
Kurtosis	-1.21	0.54
Skewness	0.32	-1.29
Range	78.25	68.61
Minimum	21.00	31.39
Maximum	99.25	100.00
Sum	1733.58	2266.80
Count	28	28

3.1.3 Distribution of scores The analysis of the distribution of health scores is provided to illustrate the differences between the two methods. This analysis cannot be used to evaluate which method is more effective because the actual distribution of range health is not known.

The distribution of range health scores differed by assessment method. The median and mode for the UFC method were 45% higher than the GMM method. The distribution difference is obvious when examining a histogram of the range health scores (Figure 1). Further quantification of the difference is provided by a negative skewness value for the UFC method and a smaller but positive skewness value for the GMM method (Table 5). Negative skewness indicates that most of the values lie to the right of the mean, while positive skewness indicates the opposite. In addition, the GMM method had negative kurtosis whereas the UFC had slight positive kurtosis. This indicates that the UFC method is characterized more by infrequent extreme deviations, while the GMM method is characterized more by frequent modest-sized deviations. The scores for both methods were considered non-normally distributed (Figure 1) using the Shapiro-Wilks test for normality ($P > 0.05$).

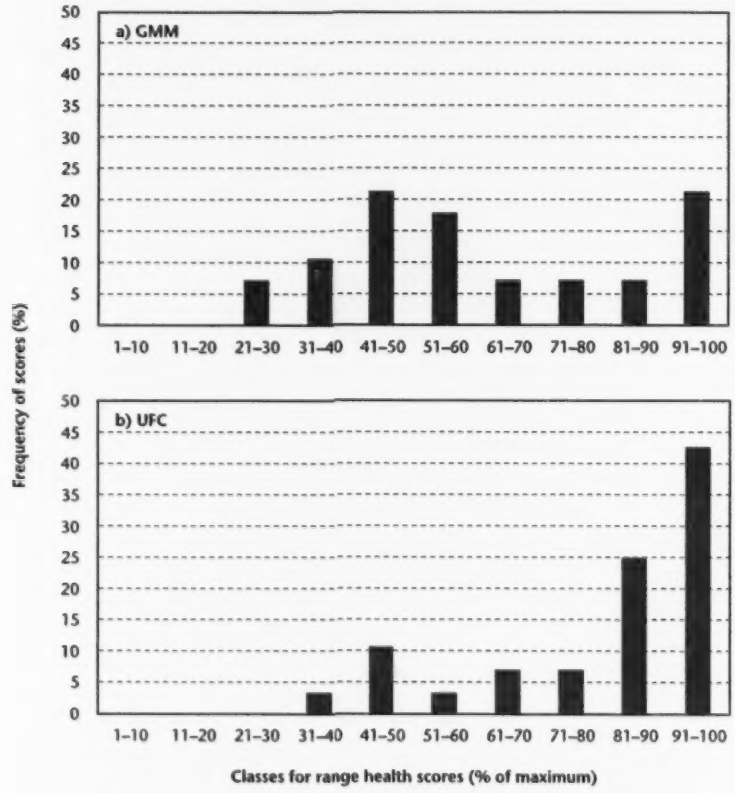

FIGURE 1 *Frequency distribution of (a) Grassland Monitoring Manual (GMM) and (b) Uplands Function Checklist (UFC) health scores evaluated at 28 treatment units in the Thompson Nicola region of British Columbia.*

Both methods utilize categories of scores that may be used to elicit a particular management action. The GMM method defines four categories, while the UFC method defines five categories (Table 6). The GMM method placed roughly the same number of treatment units in the three top categories, with one treatment unit placed in the bottom category. The UFC method placed 19 treatment units in the top category, four in each of the next two lower categories, and one in the second-lowest category. No treatments units met the criteria for the bottom category in the UFC method (Table 6).

TABLE 6 *Definition of category boundaries for the Grassland Monitoring Manual (GMM) and Uplands Function Checklist (UFC) methods, and ranking of the 28 grassland treatment units (T.U.s) in the Thompson Nicola region of British Columbia*

Method	Category name	Valid scores for category (%)	Number of T.U.s placed in category
GMM	Reference	75–100	8
GMM	Slightly altered	50–75	8
GMM	Moderately altered	25–50	11
GMM	Greatly altered	< 25	1
UFC	Proper functioning condition	≥ 80	19
UFC	Slightly at risk	61–79	4
UFC	Moderately at risk	41–60	4
UFC	Highly at risk	20–40	1
UFC	Non-functional	< 20	0

3.1.4 Relationship between the two methods The scores of the UFC method were plotted against the scores of the GMM method for each treatment unit (Figure 2). The two methods were only moderately correlated with a 47% association. The relationship was strongly curvilinear, with a linear component at the bottom end. UFC scores tended to show no relationship to GMM scores at GMM levels above 50%. Conversely, GMM scores showed no relationship to UFC scores at UFC levels above 80% (Figure 2). It is important to note that the intercept of the relationship is fairly close to zero, indicating a good match at the bottom end of the scoring. The nature of the relationship suggests that the two methods agree, in relative terms, in range health scoring of poorer treatment units but do not agree in scoring of the better treatment units.

The 28 treatment units were analyzed using PCA to identify patterns in the data based on vegetation and soil factors. Range health scores were not included in the initial ordination. The top two dimensions (eigenvectors) determined by the procedure were plotted against each other to examine potential groupings (Figure 3). The physical location of treatment units on the graph, as well as the similarity of original quantitative data associated with treatment units, was used to define groupings. Range health scores were then examined within these groups.

This process revealed three discrete groups of treatment units (Figure 3). Group 1 consisted of treatment units with high cover of rough fescue, and these received high range health scores of about 90% from both methods. Despite having almost identical average health scores for this group, however, there was only moderate relative agreement between the health assessment

methods (correlation coefficient of $r = 0.69$) (Table 7). This indicates that they were not assessing the same factors in determining the scores but arrived at the same averaged scores nonetheless.

Group 2 consisted of treatment units with high mineral soil exposure, high bulk density, and high mechanical resistance, and these received low range health scores from both methods. Despite a 13 percentage point difference in average scores for this group, there was a very high relative agreement ($r = 0.96$) between the scores (Table 7). This indicates that the methods were sensitive to the same factors (probably mineral soil exposure) but that they weighted the factors differently.

Group 3 consisted of treatment units with low rough fescue cover but high Kentucky bluegrass cover. There was poor relative agreement ($r = 0.23$) between scores and a 38 percentage point difference between average scores (Table 7). There is obvious and large disagreement between range health assessment methods on scoring of rough fescue grassland sites with a high cover of Kentucky bluegrass.

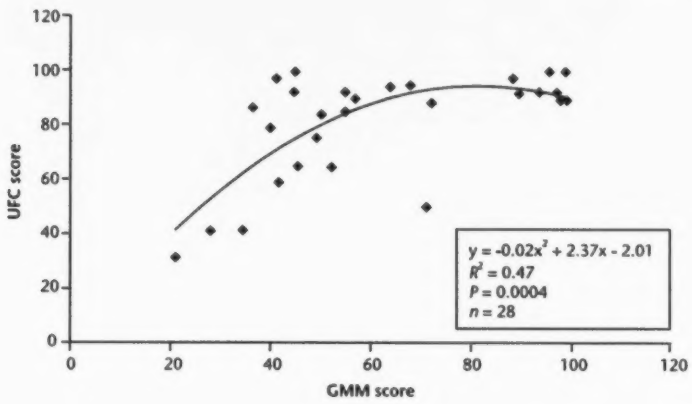

FIGURE 2 *Relationship between Uplands Function Checklist (UFC) scores and Grassland Monitoring Manual (GMM) scores at 28 grassland treatment units in the Thompson Nicola region of British Columbia.*

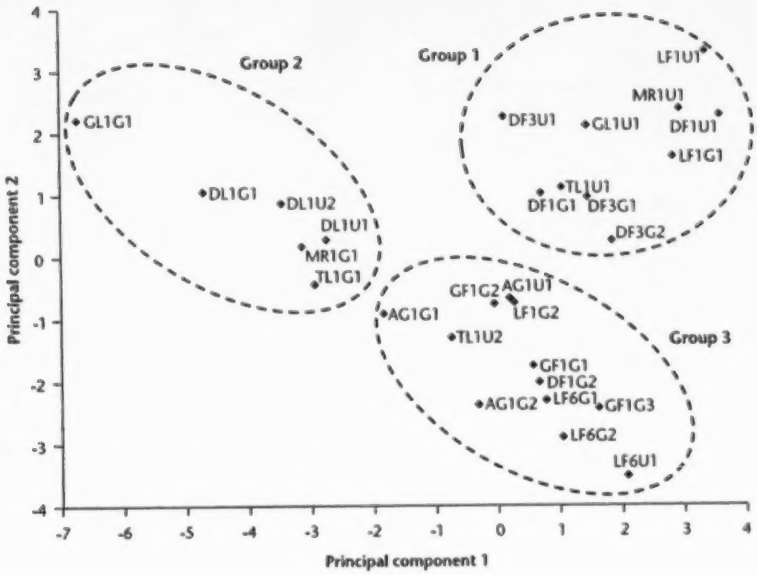

FIGURE 3 *Plot of the top two dimensions determined by principal components analysis of 28 grassland treatment units in the Thompson Nicola region of British Columbia. The full names of the treatment units are provided in Table 2.*

TABLE 7 *Selected characteristics of the three groupings of treatment units based on the top two dimensions determined by principal components analysis of 28 grassland treatment units in the Thompson Nicola region of British Columbia. GMM: Grassland Monitoring Manual; UFC: Uplands Function Checklist*

Group	UFC score	GMM score	Correlation coefficient[a] (*r*)	Rough fescue cover (%)	Kentucky bluegrass cover (%)	Mineral soil cover (%)
1	89	90	0.69	68.9	9.2	1.8
2	50	37	0.96	5.1	6.5	14.3
3	89	51	0.23	7.7	39.3	1.1

a Pearson's product-moment correlation coefficient between UFC score and GMM score within each group

3.2 Relationships of the Range Health Assessment Methods with Quantitative Variables

The range health scores were significantly related ($P < 0.05$) to nine of the 17 vegetation parameters and six of the nine physical parameters measured. The GMM and UFC methods were sensitive to the same parameters in most cases (Table 8). Microbiotic crust, bunchgrass seed heads, saturated hydraulic conductivity (K_s), soil A_h colour, and soil A_h horizon thickness were unrelated ($P > 0.05$) to either range health scoring method. Some of the measures of plant biomass and cover were also unrelated to either range health score (Table 8).

A backwards multiple regression technique was used to examine the important quantitative variables for each range health assessment method. The procedure retained six quantitative variables for the UFC method, not

including the intercept (Table 9). Two of these variables, percentage of soil C and rough fescue density, were negatively related to UFC score. Two measures of plant biomass, litter cover and soil N, were positively related to UFC score (Table 9). Although the overall adjusted correlation coefficient for the model was high (0.80), the mix of variables retained do not provide a logical explanation of UFC score. There is no obvious biological explanation why soil N and rough fescue density should result in reduced range health scores. It also seems inconsistent that rough fescue biomass increased the score while rough fescue density reduced the score. Furthermore, the retention of two correlated measures of biomass (total biomass and rough fescue biomass) is unexpected. Appendix 2 provides the correlation among all quantitative variables examined.

Only two variables were retained for the GMM score (Table 9). Of these, soil mechanical resistance was negatively related to the GMM score. Increased mechanical resistance (soil compaction) is expected to reduce range health score. Rough fescue cover was the only quantitative variable driving increases in GMM scores (Table 9). The overall model has a high adjusted correlation coefficient (0.88) and provides a logical explanation of GMM score.

TABLE 8 *Relationships among range health assessment scores and quantitative measurements taken at 28 grassland treatment units in the Thompson Nicola region of British Columbia. GMM = Grassland Monitoring Manual; UFC = Uplands Function Checklist*

	Measured property	Correlation coefficient (r^2)	
		UFC	GMM
1	Soil mechanical resistance 1.5 cm (kPa)	0.55	0.39
2	Soil mechanical resistance 4.5 cm (kPa)	0.43	0.43
3	Soil bulk density (g cm^{-3})	0.37	NS
4	Exposed mineral soil (%)	0.44	0.15
5	Soil aggregate stability (%)	0.52	0.26
6	Soil N (%)	0.36	NS
7	Soil C (%)	0.35	NS
8	Soil hydraulic conductivity (cm s^{-1})	NS	NS
9	Soil Ah colour (Munsell value)	NS	NS
10	Soil Ah thickness (cm)	NS	NS
11	Rough fescue cover (%)	0.12	0.82
12	Bluebunch wheatgrass cover (%)	NS	NS
13	Kentucky bluegrass cover (%)	0.14	0.10
14	Litter cover (%)	0.69	0.50
15	Microbiotic crust cover (%)	NS	NS
16	Total plant biomass (kg ha^{-1})	0.39	0.39
17	Rough fescue biomass (kg ha^{-1})	0.17	0.77
18	Bluebunch wheatgrass biomass (kg ha^{-1})	NS	NS
19	Invasive species biomass (kg ha^{-1})	NS	NS
20	Forb biomass (kg ha^{-1})	NS	NS
21	Other grasses biomass (kg ha^{-1})	NS	NS
22	Litter biomass (kg ha^{-1})	0.17	0.43
23	Rough fescue density (m^{-2})	0.11	0.71
24	Bluebunch wheatgrass density (m^{-2})	0.12	NS
25	Rough fescue seed heads (m^{-2})	NS	NS
26	Bluebunch wheatgrass seed heads (m^{-2})	NS	NS
27	Plant species richness (5 m^{-2})	0.11	0.18

NS = non-significant relationship

TABLE 9 *Variables retained using backwards multiple regression analysis of range health assessment scores to 27 quantitative variables taken at 28 grassland treatment units in the Thompson Nicola region of British Columbia. GMM = Grassland Monitoring Manual method; UFC = Uplands Function Checklist*

Range health score	Quantitative variable	Estimate	Prob. > t	Adj. R^2
UFC score	Rough fescue density (m^{-2})	-13.21	0.0006	0.80
UFC score	Rough fescue biomass ($kg \cdot ha^{-1}$)	1.03	0.0005	
UFC score	Total plant biomass ($kg \cdot ha^{-1}$)	0.24	0.0411	
UFC score	Litter cover (%)	1.06	< 0.0001	
UFC score	Soil N (%)	148.4	0.0051	
UFC score	Soil C (%)	-11.75	0.0109	
UFC score	Intercept	-28.77	0.0774	
GMM score	Rough fescue cover (%)	0.58	< 0.0001	0.88
GMM score	Soil mechanical resistance (kPa)	-0.02	0.0007	
GMM score	Intercept	58.22	< 0.0001	

3.2.1 Soil mechanical resistance Soil mechanical resistance was always negatively related to both range health assessments, especially at soil depths closer to the surface (1.5 and 4.5 cm) (Table 10). Soil mechanical resistance[1] was measured down to a 15-cm depth at intervals of 1.5 cm, and there were also significant relationships at deeper soil depths (data not shown); however, the coefficients of determination (R^2) with health scores were highest for the two top soil depths, and only these will be presented.

The strongest relationships between individual health scores and mechanical resistance at 1.5 cm soil depth are presented graphically to illustrate the difference between the methods (Figures 4 and 5). The UFC scores were more closely associated ($R^2 = 0.55$) with mechanical resistance at 1.5 cm soil depth than were the GMM scores ($R^2 = 0.39$). The UFC scores were linearly related to mechanical resistance, which is a beneficial trait for an assessment method when the categories consist of equal size classes (Figure 4). The relationship of the GMM scores to mechanical resistance was clearly curvilinear (Figure 5; Table 10). These relationships held the same shapes at the 4.5 cm soil depth (Table 10).

1 Soil mechanical resistance was determined at the various grassland treatment units over a 28-day period from June 2 through June 30. Since mechanical resistance values were not corrected for soil moisture, it is possible that error was introduced due to soil moisture differences alone. Increasing soil moisture reduces soil mechanical resistance. Soil moisture levels are more likely to be comparable between adjacent grazed and ungrazed treatment units at one site, making such comparisons more valid.

TABLE 10 *Relationships among range health assessment scores and soil mechanical resistance at 1.5 and 4.5 cm depths taken at 28 grassland treatment units in the Thompson Nicola region of British Columbia. GMM = Grassland Monitoring Manual method; UFC = Uplands Function Checklist*

Independent variable	Dependent variable	R^2	*n*	*P* value	Equation
GMM	Mechanical resistance at 1.5 cm	0.21	28	0.0129	$y = -2.6x + 343.9$
GMM	Mechanical resistance at 1.5 cm	0.39	28	0.0022	$y = 0.12x^2 - 17.9x + 776.4$
UFC	Mechanical resistance at 1.5 cm	0.55	28	< 0.0001	$y = -5.18x + 600.6$
GMM	Mechanical resistance at 4.5 cm	0.28	28	0.0037	$y = -8.7x + 1415.5$
GMM	Mechanical resistance at 4.5 cm	0.43	28	0.0010	$y = 0.3x^2 - 49.8x + 2576.9$
UFC	Mechanical resistance at 4.5 cm	0.43	28	0.0001	$y = -1339.3x + 1958.4$

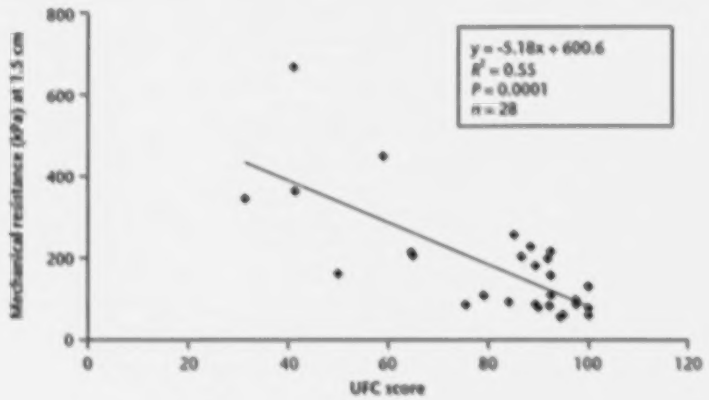

FIGURE 4 *Soil mechanical resistance at 1.5 cm soil depth as related to Uplands Function Checklist (UFC) scores taken at 28 grassland treatment units in the Thompson Nicola region of British Columbia.*

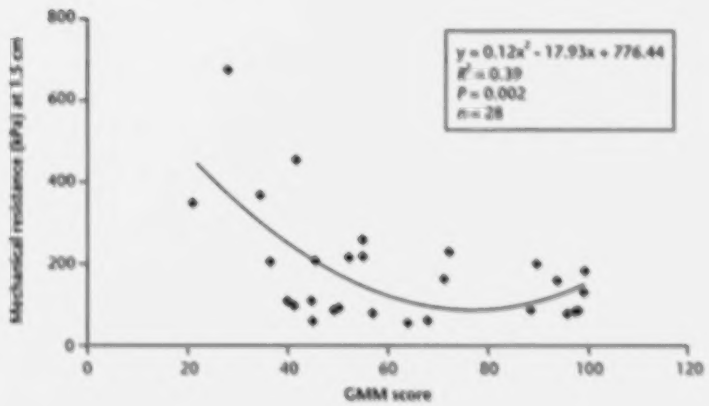

FIGURE 5 *Soil mechanical resistance at 1.5 cm soil depth as related to Grassland Monitoring Manual (GMM) scores taken at 28 grassland treatment units in the Thompson Nicola region of British Columbia.*

3.2.2 Soil bulk density Bulk density was unrelated ($P > 0.10$) to the GMM scores but was strongly negatively related ($P = 0.0006$) to the UFC scores (Figure 6). Soil compaction, as measured by bulk density, decreased with increasing UFC scores. The relationship was linear, producing a good dispersion of the bulk density values. Only 37% of the variation in bulk density was explained by the UFC scores, with a large amount of the unexplained variation occurring at the higher UFC scores (Figure 6). Soil bulk density also varies with texture and organic matter content, so some of the unexplained variation could be from treatment units that were sandier than average or that had lower organic matter content.

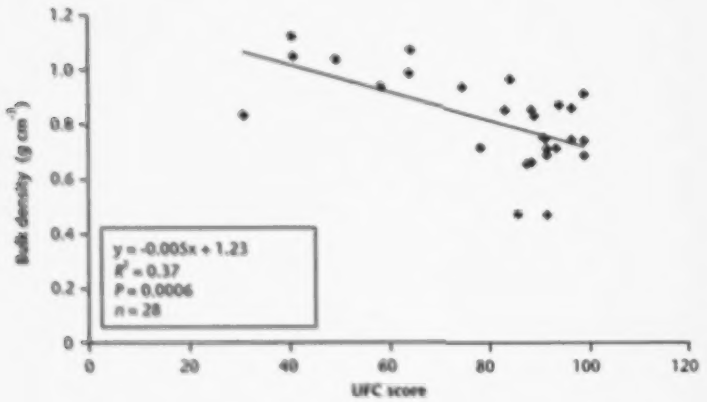

FIGURE 6 *Soil bulk density to 7.5 cm soil depth as related to Uplands Function Checklist (UFC) scores taken at 28 grassland treatment units in the Thompson Nicola region of British Columbia.*

3.2.3 Exposed mineral soil There was a negative relationship ($P < 0.0001$) between exposed mineral soil and both range health assessment methods. Exposed mineral soil decreased with increasing range health scores. The association was quite weak (15%) with the GMM method (Figure 7) and moderately strong (44%) with the UFC method (Figure 8). The dispersion of exposed mineral soil values was relatively good for the GMM method but was concentrated at one end for UFC method.

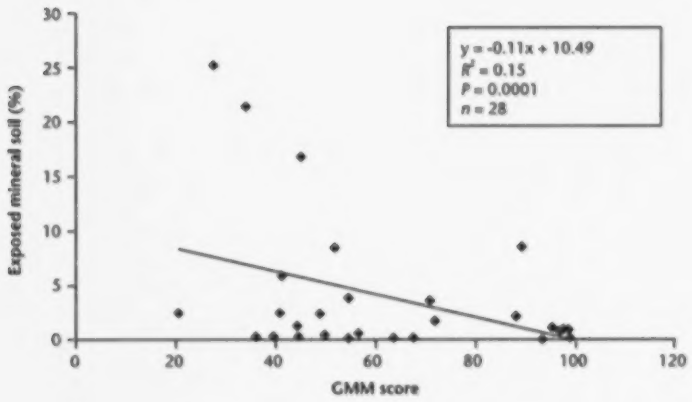

FIGURE 7 *Exposed mineral soil as related to Grassland Monitoring Manual (GMM) scores taken at 28 grassland treatment units in the Thompson Nicola region of British Columbia.*

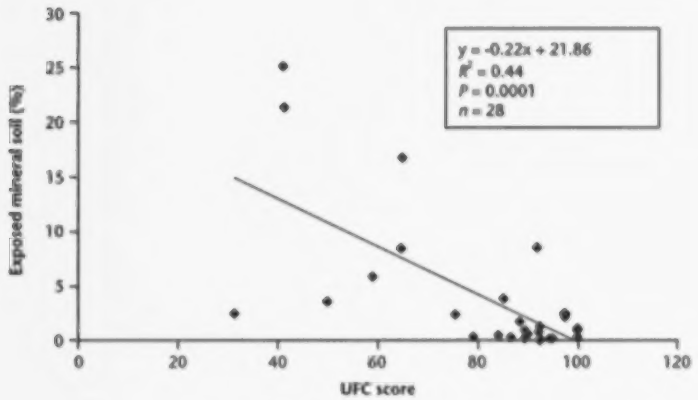

FIGURE 8 *Exposed mineral soil as related to Uplands Function Checklist (UFC) scores taken at 28 grassland treatment units in the Thompson Nicola region of British Columbia.*

3.2.4 Soil aggregate stability Percentage of water stable aggregates was strongly positively related ($P < 0.0001$) to UFC score. Fifty-two percent of the variation in water stable aggregates was predicted by UFC score (Figure 9). Percentage of water stable aggregates was also positively related to GMM score ($P = 0.028$); however, only 26% of the variation was explained by the GMM score (Figure 10).

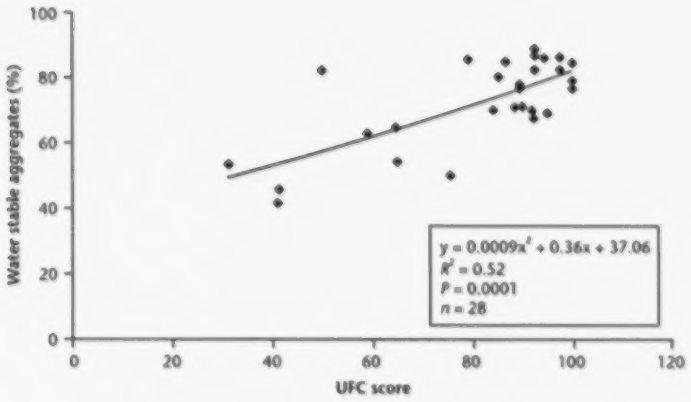

FIGURE 9 *Water stable aggregates as related to Uplands Function Checklist (UFC) scores taken at 28 grassland treatment units in the Thompson Nicola region of British Columbia.*

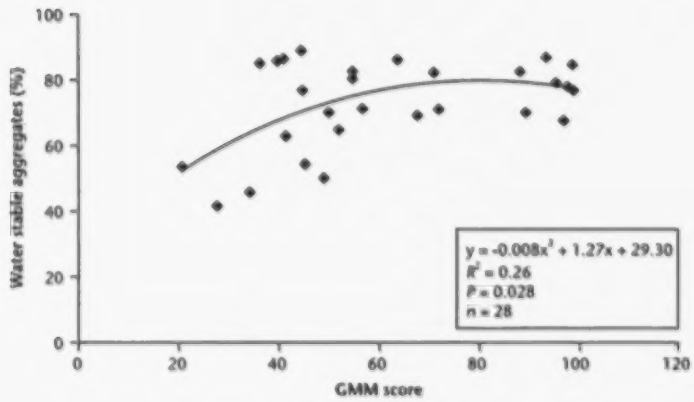

FIGURE 10 *Water stable aggregates as related to Grassland Monitoring Manual (GMM) scores taken at 28 grassland treatment units in the Thompson Nicola region of British Columbia.*

3.2.5 Total soil nitrogen and carbon Total soil nitrogen and carbon in the top 7.5 cm of soil were both positively related to UFC score ($P < 0.001$) (Figures 11 and 12). There were no significant relationships ($P > 0.10$) with GMM score.

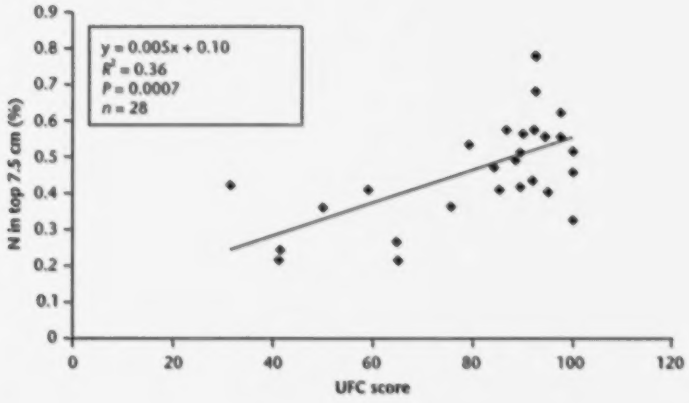

FIGURE 11 *Total nitrogen in the top 7.5 cm of soil as related to Uplands Function Checklist (UFC) scores taken at 28 grassland treatment units in the Thompson Nicola region of British Columbia.*

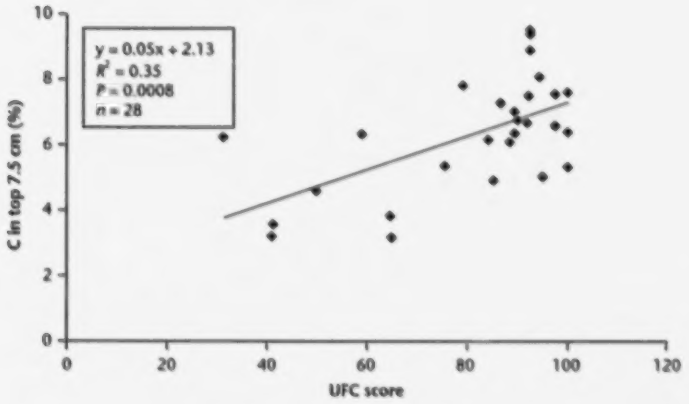

FIGURE 12 *Total carbon in the top 7.5 cm of soil as related to Uplands Function Checklist (UFC) scores taken at 28 grassland treatment units in the Thompson Nicola region of British Columbia.*

3.2.6 Rough fescue cover Rough fescue cover was strongly positively related ($P < 0.0001$) to the GMM method, which is not surprising since 40% of the GMM rating is derived from an assessment of key bunchgrass cover (rough fescue, Idaho fescue, and bluebunch wheatgrass). Increasing GMM score was associated with increasing rough fescue cover (Figure 13). GMM score explained 82% of the variation in rough fescue cover. Rough fescue cover is not useful for GMM scoring below about 40%. The relationship was strictly linear.

Rough fescue cover was weakly related ($P = 0.073$) to the UFC method (Figure 14). The UFC score explained only 12% of the variation associated with rough fescue cover. As with the GMM method, rough fescue cover was not useful at the lowest UFC scores.

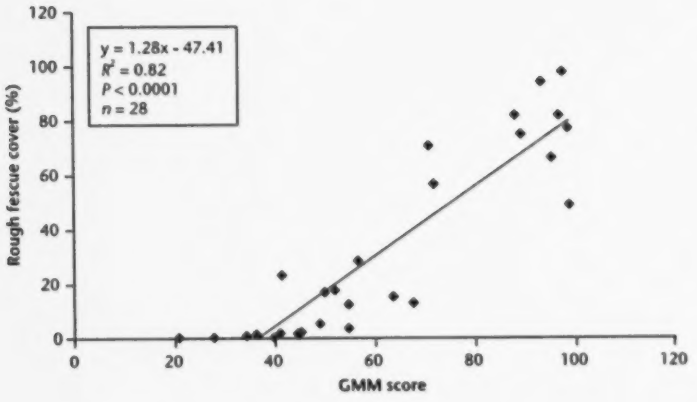

FIGURE 13 *Rough fescue cover as related to Grassland Monitoring Manual (GMM) scores taken at 28 grassland treatment units in the Thompson Nicola region of British Columbia.*

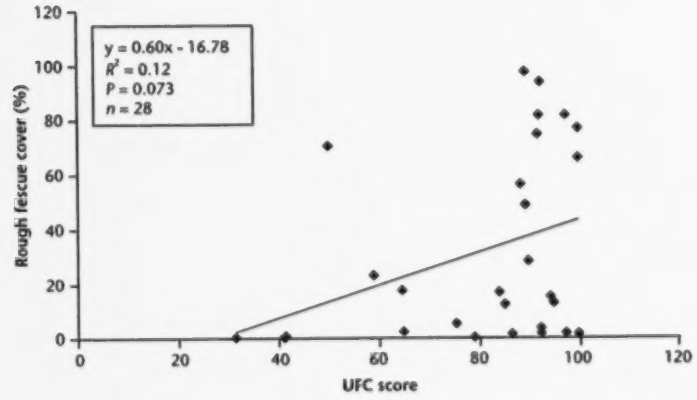

FIGURE 14 *Rough fescue cover as related to Uplands Function Checklist (UFC) scores taken at 28 grassland treatment units in the Thompson Nicola region of British Columbia.*

3.2.7 Kentucky bluegrass cover Kentucky bluegrass cover was only weakly related to both range health assessment methods; however, it is notable that the relationship was negative for GMM (Figure 15) and positive for UFC (Figure 16). Increasing GMM score was associated with decreasing Kentucky bluegrass cover (Figure 15). This is consistent with the expected occurrence of Kentucky bluegrass in early seral rough fescue plant communities. In contrast, increasing UFC score was associated with increasing Kentucky bluegrass cover (Figure 16).

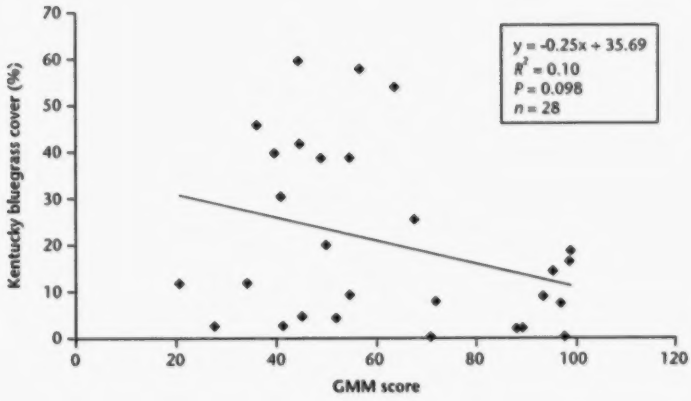

FIGURE 15 *Kentucky bluegrass cover as related to Grassland Monitoring Manual (GMM) scores taken at 28 grassland treatment units in the Thompson Nicola region of British Columbia.*

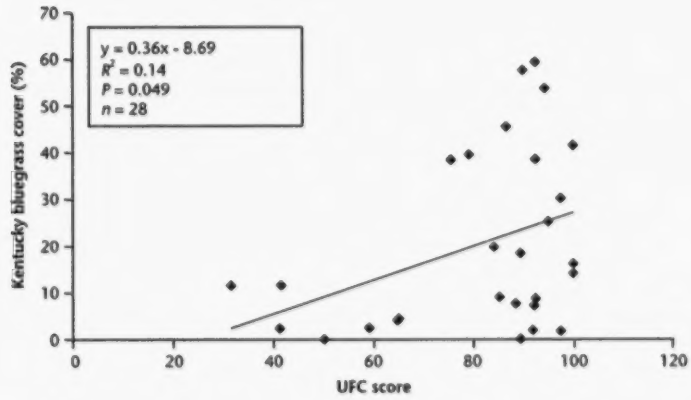

FIGURE 16 *Kentucky bluegrass cover as related to Uplands Function Checklist (UFC) scores taken at 28 grassland treatment units in the Thompson Nicola region of British Columbia.*

3.2.8 Litter cover Litter cover was strongly positively related to both GMM and UFC score ($P < 0.001$). This is likely because litter cover is directly assessed by two questions or more, and scores are heavily weighted by both of the health assessments. The GMM score explained 50% of the variation in litter cover, while the UFC scored explained 70% of the variation. A curvilinear polynomial fit was best suited to both health assessment scores (Figures 17 and 18).

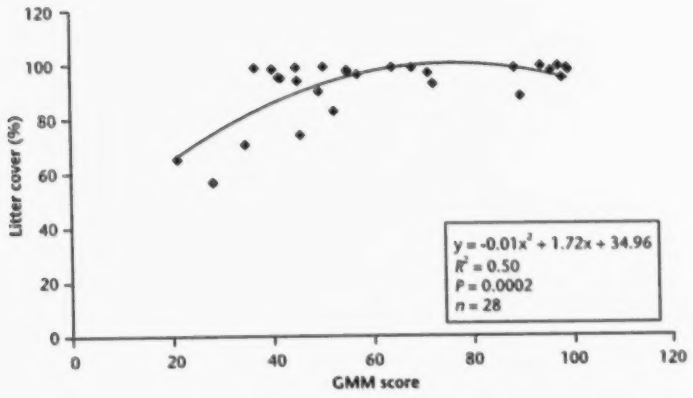

FIGURE 17 *Litter cover as related to Grassland Monitoring Manual (GMM) scores taken at 28 grassland treatment units in the Thompson Nicola region of British Columbia.*

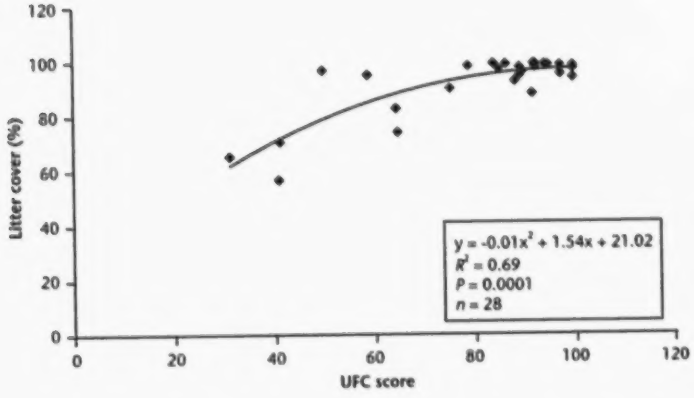

FIGURE 18 *Litter cover as related to Uplands Function Checklist (UFC) scores taken at 28 grassland treatment units in the Thompson Nicola region of British Columbia.*

3.2.9 Total above-ground biomass GMM and UFC score were both closely related to total above-ground biomass (Figures 19 and 20). Both GMM and UFC score explained 39% of the variation of total above-ground biomass.

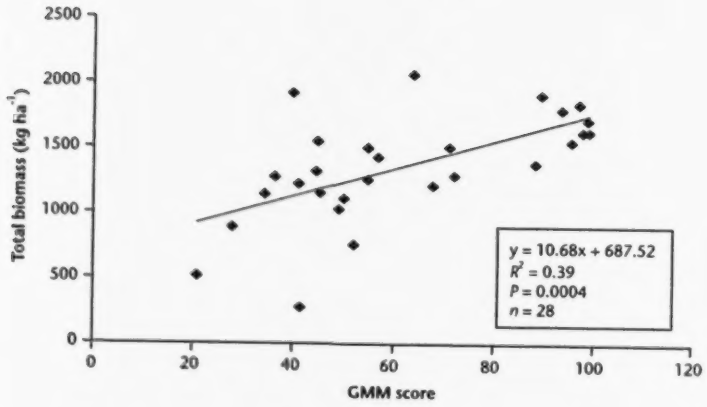

FIGURE 19 *Total above-ground biomass as related to Grassland Monitoring Manual (GMM) scores taken at 28 grassland treatment units in the Thompson Nicola region of British Columbia.*

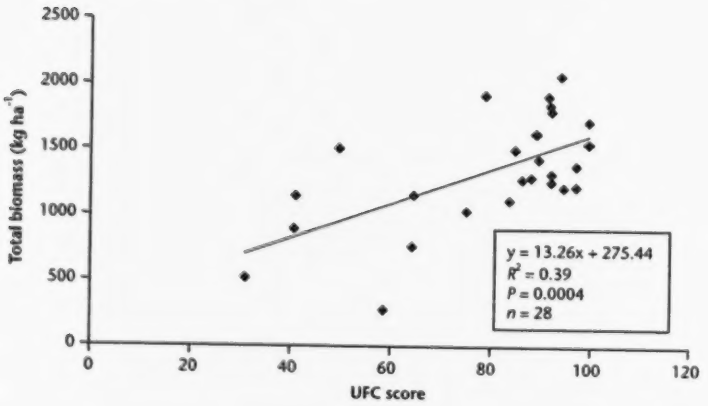

FIGURE 20 *Total above-ground biomass as related to Uplands Function Checklist (UFC) cores taken at 28 grassland treatment units in the Thompson Nicola region of British Columbia.*

3.2.10 Rough fescue biomass Rough fescue above-ground biomass was strongly positively related ($P < 0.0001$) to GMM score, in a very similar fashion as the relationship with rough fescue cover. Again, this was not unexpected, given the reliance of GMM scoring on the presence of key bunchgrasses. Seventy-seven percent of the variation in rough fescue biomass was predicted by GMM score (Figure 21). Rough fescue biomass was also positively related to UFC score; however, much less variation (17%) was explained by UFC score (Figure 22).

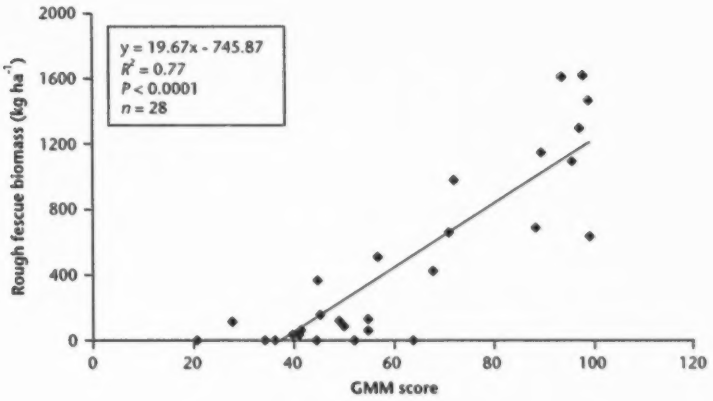

FIGURE 21 *Rough fescue biomass as related to Grassland Monitoring Manual (GMM) scores taken at 28 grassland treatment units in the Thompson Nicola region of British Columbia.*

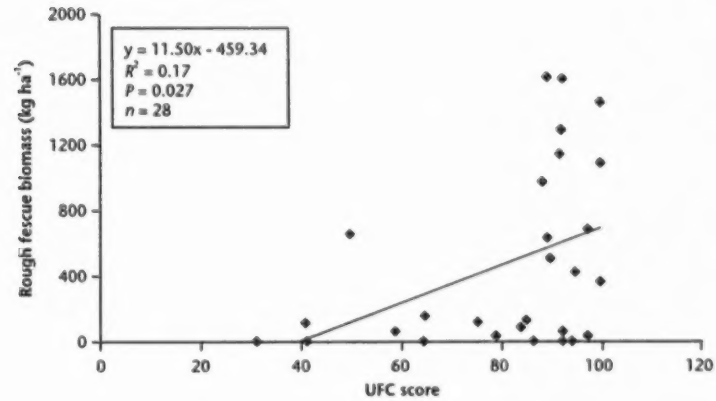

FIGURE 22 *Rough fescue biomass as related to Uplands Function Checklist (UFC) scores taken at 28 grassland treatment units in the Thompson Nicola region of British Columbia.*

3.2.11 Litter biomass Litter biomass was strongly positively related ($P < 0.0002$) to GMM score. Forty-three percent of the variation in litter biomass was predicted by GMM score (Figure 23). Litter biomass was also positively related to UFC score ($P = 0.027$); however, only 17% of the variation was explained by UFC score (Figure 24).

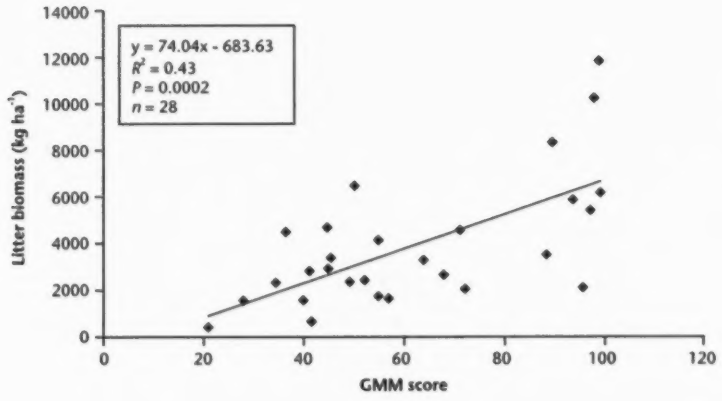

FIGURE 23 *Litter biomass as related to Grassland Monitoring Manual (GMM) scores taken at 28 grassland treatment units in the Thompson Nicola region of British Columbia.*

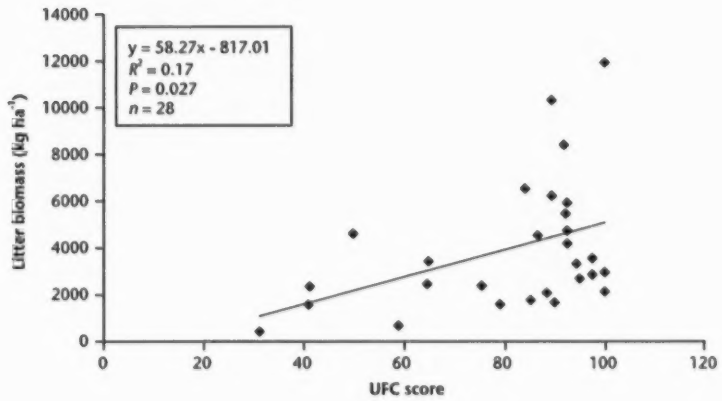

FIGURE 24 *Litter biomass as related to Uplands Function Checklist (UFC) scores taken at 28 grassland treatment units in the Thompson Nicola region of British Columbia.*

3.2.12 Rough fescue density For the purposes of this study, large rough fescue were defined as plants with diameters greater than 4 cm. The density of large rough fescue plants was strongly positively related ($P < 0.0001$) to GMM score. Seventy-one percent of the variation in rough fescue density was predicted by GMM score (Figure 25). Rough fescue density was weakly positively related to UFC score ($P = 0.091$); however, only 11% of the variation was explained by UFC score (Figure 26). Relationships of small rough fescue density and range health scores had similar patterns as those for large rough fescue but with weaker associations (R^2).

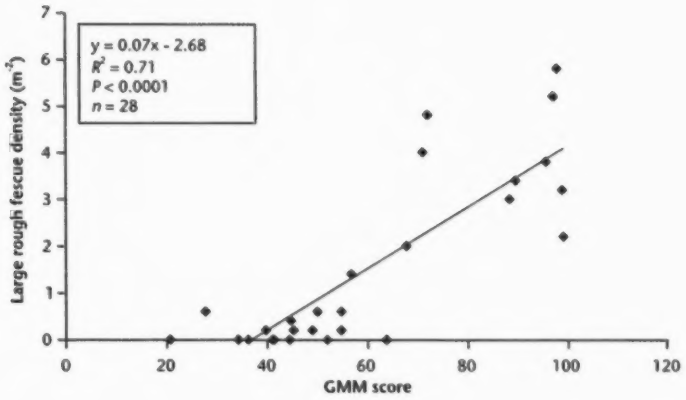

FIGURE 25 *Density of large rough fescue plants as related to Grassland Monitoring Manual (GMM) scores taken at 28 grassland treatment units in the Thompson Nicola region of British Columbia.*

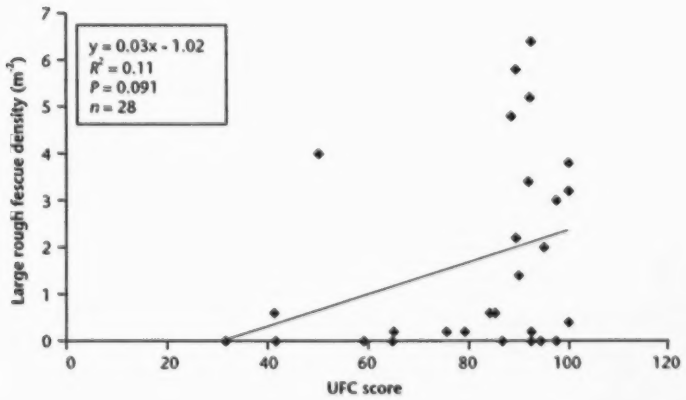

FIGURE 26 *Density of large rough fescue plants as related to Uplands Function Checklist (UFC) scores taken at 28 grassland treatment units in the Thompson Nicola region of British Columbia.*

3.2.13 Bluebunch wheatgrass density The density of total bluebunch wheatgrass plants was weakly negatively related to UFC score ($P = 0.068$) and explained only 12% of the variation (Figure 27). Increasing bluebunch wheatgrass density reduced the UFC score. Bluebunch wheatgrass density was not related to GMM score.

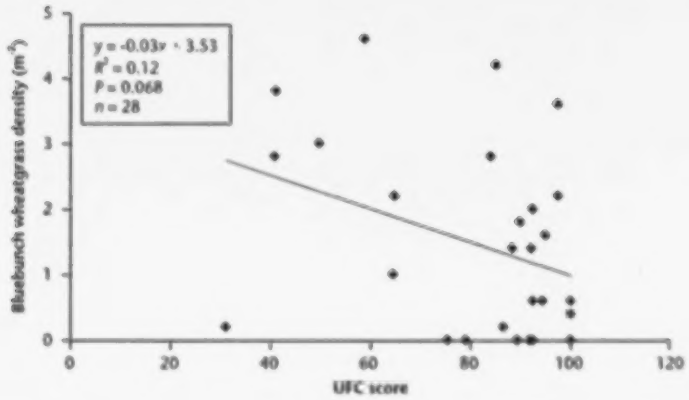

FIGURE 27 *Density of bluebunch wheatgrass plants as related to Uplands Function Checklist (UFC) scores taken at 28 grassland treatment units in the Thompson Nicola region of British Columbia.*

3.2.14 Plant species richness Species richness had a weak curvilinear relationship ($P < 0.09$) with GMM score, first increasing then decreasing with higher scores (Figure 28). This kind of relationship is not unexpected because it supports the intermediate disturbance hypothesis first proposed by Connell (1978). Undisturbed plant communities are subject to competitive exclusion by the dominant species. With high disturbance, only species that are tolerant of the stress can persist. Intermediate levels of disturbance are thought to support the highest diversity.

Species richness did not show this same relationship with UFC score (Figure 29), perhaps because the UFC score utilizes less plant community information.

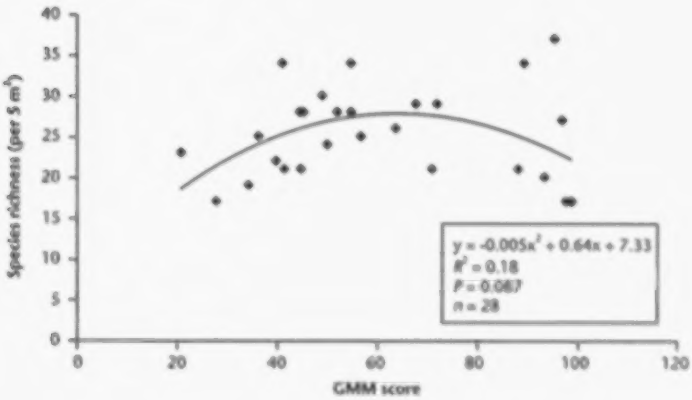

FIGURE 28 *Plant species richness as related to Grassland Monitoring Manual (GMM) scores taken at 28 grassland treatment units in the Thompson Nicola region of British Columbia.*

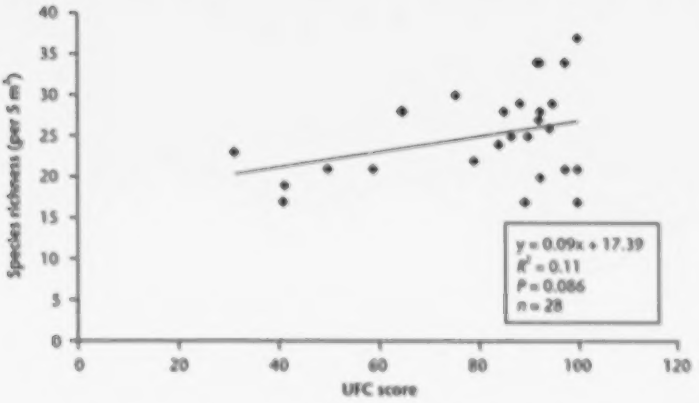

FIGURE 29 *Plant species richness as related to Uplands Function Checklist (UFC) scores taken at 28 grassland treatment units in the Thompson Nicola region of British Columbia.*

4 DISCUSSION

The two range health assessment methods were somewhat sensitive to many of the quantitative measures taken at the 28 treatment units. Fifteen of the 26 quantitative measures used in this study were found to be related to the range health scores. The relationships with quantitative measures were almost always consistent with expected ecosystem-level responses to natural disturbances and grazing management. For example, treatment units with high soil compaction, as measured by soil bulk density or mechanical resistance, received low range health scores, as would be expected. This can also be described as a negative relationship where increasing soil compaction results in decreasing range health scores. The two range health assessment methods almost always had the same direction (sign) of relationship with a particular quantitative measure (i.e., both positively correlated or both negatively correlated).

The interpretation of the results of this study depends, to a large extent, on how range health is defined quantitatively. The selection of quantitative measures that were tested was somewhat subjective because many other possible measures exist that were not included. Nonetheless, the level of agreement between the range health assessment methods as well as the consistency of the range health scores with ecological principles provides a high level of confidence that the results of this study are valid.

The UFC method was significantly correlated (i.e., sensitive) to 15 quantitative measures, while the GMM method was significantly correlated to 11. For the 11 quantitative measures to which both were correlated, the UFC method noticeably explained more of the variation (R^2) in soil mechanical resistance, exposed mineral soil, water stable aggregates, and litter cover, while the GMM method noticeably explained more of the variation in rough fescue cover, rough fescue biomass, rough fescue density, and litter biomass. The UFC method is therefore more sensitive to quantitative measurements that are

intended to describe the range health criteria for assessing the degree of soil and site stability (criterion #1) and hydrologic function (criterion #2), while the GMM method is more sensitive to criterion #3 (biotic integrity) (Table 1).

Based on very strong correlations with measures of rough fescue, and overall weakness in comparison to the UFC method for most other measures, the GMM method appears to be biased toward plant community information. A maximum of 57% of the total score can be derived from plant community information (criterion #3), while a maximum of only 17% and 15% can be derived from criterion #1 and #2, respectively. While there is no "true" definition of range health, nor a necessity to weight the three criteria equally, the lack of sensitivity to bulk density, soil carbon, and soil nitrogen when using the GMM could be a concern at some sites.

The UFC produces a better balance among the three criteria than does the GMM method; however, the UFC method seems too weak in assessing plant community information derived from the dominant plant in the rough fescue grasslands—rough fescue. Correlation coefficients among UFC scoring and rough fescue density, rough fescue cover, and rough fescue biomass were low, ranging from 0.11 to 0.17. Examination of the scoring sheet for the UFC methods reveals that a maximum of 29% can be derived from plant community (criterion #3) information.

When plotted against each other, the two methods were moderately correlated with a 47% association. The shape of the relationship suggests that the two methods agree, in relative terms, in range health scoring of poor sites but do not agree in scoring of better sites. A PCA also showed very good agreement between the two methods at the poor sites. The PCA, however, separated the better sites into two groups based on the presence of Kentucky bluegrass versus rough fescue. Based on this analysis, it is clear that a major difference in scoring between the two methods occurs on rough fescue grassland sites with high Kentucky bluegrass cover. This is a significant problem because Kentucky bluegrass is a fairly common component of many rough fescue grassland sites in British Columbia.

The data sets provided by this study offer the opportunity for further refinement of both methods by:

1. re-alignment of the range health scores in a manner that increases (or decreases) the correlation with relevant quantitative measures provided by the study. For example, the GMM method may yield improved sensitivity to a greater number of quantitative measures if the scoring weight for rough fescue is reduced. Shifting the relative emphasis (scoring weight) of the range health questions is critical to providing a balanced overall range health assessment.
2. removal or addition of questions in a manner that improves on any weaknesses identified by the study. There may be questions that are routinely found to be difficult to assess reliably. Removal or modification of these questions and/or addition of more discerning ones may shift the overall score in a manner that better aligns with the quantitative measures.

5 CONCLUSIONS

Even though the two range health assessment methods rely on visual ratings, they were both quite sensitive to the state of the 28 rough fescue grassland sites used in this study. Both methods were found to be equally repeatable by samplers and were correlated to most of the selected quantitative measures of range health.

The methods did not agree completely in their assessments of range health of the 28 treatment units examined. A better agreement between the two methods was achieved in range health scoring of poor sites but methods did not agree in scoring of better sites, especially those with a high component of Kentucky bluegrass. This is due to a different emphasis on degree of soil and site stability by the UFC method versus an emphasis on biotic integrity by the GMM method.

There were potential weaknesses identified for both methods. The GMM method appears to be too heavily weighted towards plant community information, while the UFC method may benefit from increased plant community information, especially for rough fescue.

6 LITERATURE CITED

Angers, D.A. and G.R. Mehuys. 1993. Aggregate stability to water. In: Soil sampling and methods of analysis. M.R. Carter (editor). Lewis Publ., Boca Raton, Fla., pp. 651–658.

B.C. Ministry of Forests. 1997. Range and riparian assessment reference manual. For. Pract. Br., Range Section, Victoria, B.C.

B.C. Ministry of Forests and Range. 2005. Southern Interior Forest Region range reference areas. South. Interior. For. Region, Kamloops, B.C. www.for.gov.bc.ca/rsi/range/RRA/intro.htm (Accessed May 11, 2006).

Blake, G.R. and K.H. Hartge. 1986. Bulk density. In: Methods of soil analysis. Part 1. Physical and mineralogical methods. A. Klute (editor). Agronomy Monogr. 9, Am. Soc. Agronomy, Madison, Wis., pp. 363–375.

Bradford, J.M. 1986. Penetrability. In: Methods of soil analysis. Part 1. Physical and mineralogical methods. A. Klute (editor). Agronomy Monogr. 9 Am. Soc. Agronomy, Madison, Wis., pp. 436–478.

Clements, F.E. 1920. Plant indicators: the relation of plant communities to process and practice. Carnegie Inst., Washington, D.C.

Connell, J.H. 1978. Diversity in tropical rain forests and coral reefs. Science 199:1302–1310.

Daubenmire, R. 1959. A canopy-coverage method of vegetation analysis. N.W. Sci. 33:43–65.

Douglas, G.W., G.B. Straley, D. Meidinger, and J. Pojar (editors). 1998–2001. Illustrated flora of British Columbia. B.C. Min. Environ., Lands and Parks and B.C. Min. For., Victoria, B.C.

Dyksterhuis, E.J. 1949. Condition and management of rangeland based on quantitative ecology. J. Range Manag. 2:104–115.

Galbraith, W.A. and E.W. Anderson. 1971. Grazing history of the Northwest. J. Range Manag. 24:6–12

Gregorich, E.G., M.R. Carter, D.A. Angers, C.M. Monreal, and B.H. Ellert. 1994. Towards a minimum data set to assess soil organic matter quality in agricultural soils. Can. J. Soil Sci. 74: 367–385.

Gupta, R.C. and S. Ma. 1996. Testing the equality of coefficients of variation in k normal populations. Communications in Statistics—Theory and Methods 25:115–132.

Herrick, J.E., J.R. Brown, A.J. Tugel, P.L. Shaver, and K.M. Havstad. 2002. Application of soil quality to monitoring and management: paradigms from rangeland ecology. Agronomy J. 94:3–11.

Lloyd, D.K., K. Angove, G. Hope, and C. Thompson. 1990. A guide to site interpretation for the Kamloops Forest Region. B.C. Min. For., Res. Br., Victoria, B.C. Land Manag. Rep. 23.

Magurran, A.E. 1988. Ecological diversity and its measurement. Princeton Univ. Press, Princeton, N.J.

McGill, W.B. and C.T. Figueiredo. 1993. Total nitrogen. In: Soil sampling and methods of analysis. M.R. Carter (editor). Can. Soc. Soil Sci., Lewis Publ., Boca Raton, Fla., pp. 201–211.

McLean, A. 1982. History of the cattle industry in British Columbia. Rangelands 4:130–134.

Munsell Soil Color Charts. 2000. Year 2000 revised edition. Munsell Color. Gretbag Macbeth, New Windsor, N.Y.

National Research Council (NRC). 1994. Rangeland health. New methods to classify, inventory and monitor rangelands. Washington, D.C.

Nelson, D.W. and L.E. Sommers. 1996. Total carbon, organic carbon and organic matter. In: Methods of soil analysis. Part 3—Chemical methods. D.L. Sparks, A.L. Page, P.A. Helmke, R.H. Loeppert, P.N. Soltanpour, M.A.Tabatabai, C.T. Johnson, and M.E. Sumner (editors). Soil Sci. Soc. Am. Book Ser. 5. SSSA, Madison, Wis., pp. 961–1010.

Nimmo, J.R. and K.S. Perkins. 2002. Aggregate stability and size distribution. In: Methods of soil analysis. Part 4—Physical methods. A.J.H. Dane and G.C. Topp (editors). Soil Sci. Soc. Am. Book Ser. 5. SSSA, Madison, Wis., pp. 317–328.

Pyke, D.A., J.E. Herrick, P. Shaver, and M. Pellant. 2002. Rangeland health attributes and indicators for qualitative assessment. J. Range Manag. 55:584–597.

SAS Institute Inc. 2003. SAS/STAT user's guide. Version 6, 4th ed., Cary, N.C.

Wikeem, B. and S. Wikeem. 2005. Grassland assessment manual for British Columbia: a prototype for the fescue grasslands of the Nicola Valley. Version 2. Grasslands Conservation Council of B.C., Kamloops, B.C.

Zhang, R. 1997. Determination of soil sorptivity and hydraulic conductivity from the disk infiltrometer. Soil Sci. Soc. Am. J. 61:1024–1030.

APPENDIX 1 Canopy cover (%) of vascular plant species at 28 grassland treatment units in the Thompson Nicola region of British Columbia.

Scientific name	Treatment unit name[a]																											
	AG1U1	AG1G1	AG1G2	DL1U1	DL1U2	DL1G1	DF1U1	DF1G1	DF1G2	DF3U1	DF3G1	DF3G2	GF1G3	GF1G1	GF1G2	GL1U1	GL1G1	LF1U1	LF1G1	LF1G2	LF6U1	LF6G1	LF6G2	MR1U1	MR1G1	TL1U2	TL1U1	TL1G1
Achillea millefolium	2	3	2	2	12	2	0	3	7	1	3	2	1	4	6	2	1	0	4	1	2	19	3	2	5	7	1	7
Achnatherum nelsonii	5	2	4	0	0	0	1	3	2	0	1	1	10	15	5	0	10	0	0	0	3	6	9	0	4	4	0	7
Achnatherum richardsonii	6	0	1	0	0	0	1	6	2	0	0	0	3	0	4	2	0	0	0	1	0	0	0	0	0	14	8	22
Agoseris glauca	4	3	0	2	0	0	0	0	1	0	0	0	0	0	0	5	0	2	10	16	9	27	2	4	0	0	0	0
Agropyron cristatum	0	0	0	0	3	1	0	0	0	0	0	0	0	0	0	0	0	0	1	4	0	0	0	0	0	1	0	1
Allium cernuum	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	3	1	3	0	0	0	0	0
Antennaria sp.	2	3	1	1	0	1	0	2	0	1	0	6	0	1	0	2	8	0	0	0	0	0	0	0	26	1	0	8
Aster campestris	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	4	5	0	3	1	2	2	4
Astragalus miser	5	10	5	0	0	0	3	9	0	3	7	2	1	3	0	0	0	0	5	0	1	2	2	0	5	0	0	0
Balsamorhiza sagittata	0	0	0	0	0	0	2	0	0	7	17	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0
Bromus inermis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	13	0
Bromus tectorum	0	0	0	1	8	1	0	0	4	0	0	2	0	0	3	0	0	0	0	1	0	0	0	0	0	0	0	0
Centaurea biebersteinii	12	23	27	3	3	3	0	0	0	0	0	0	1	1	2	0	0	0	0	5	0	0	5	0	0	0	0	0
Cerastium arvense	0	0	1	0	0	0	0	1	1	0	0	3	0	0	0	0	0	0	0	0	1	0	0	0	0	7	0	5
Crepis atribarba	0	0	0	0	0	0	0	0	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Eriogonum heracleoides	0	0	0	2	7	3	1	2	0	1	0	2	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0
Festuca campestris	13	12	2	17	2	1	94	56	28	70	81	66	15	1	0	74	0	97	81	17	1	1	3	77	23	5	48	0
Festuca idahoensis	0	0	0	8	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3	0	0	0
Galium boreale	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	7	1	0	0	0	0	0
Geum triflorum	0	0	0	1	0	0	0	0	0	1	0	1	0	0	0	6	0	0	0	0	0	0	0	5	3	1	0	0
Hesperostipa comata	0	1	0	0	0	0	0	0	1	0	0	0	0	10	29	0	0	0	3	26	1	0	1	0	0	0	0	0
Juncus balticus	0	0	0	0	0	0	0	0	0	0	0	5	0	1	0	0	0	0	0	0	13	31	22	0	0	0	0	0
Koeleria macrantha	6	9	11	29	10	14	0	3	0	2	6	2	8	8	4	3	5	0	1	3	0	0	1	1	9	4	0	8
Lithospermum ruderale	1	3	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	2	0	1	0	0	0	0	0
Lupinus sericeus	0	0	0	5	11	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	1	0	0	0
Poa pratensis	25	9	30	4	4	12	9	8	58	0	2	14	54	41	39	2	2	0	7	20	59	46	38	16	2	38	18	12
Poa secunda	0	0	0	8	5	18	0	0	0	0	0	0	0	0	0	0	15	0	0	0	2	0	0	0	10	0	0	0
Pseudoroegneria spicata	21	26	23	6	12	14	1	10	5	17	15	3	13	1	2	2	8	0	3	13	5	2	7	0	3	6	0	0
Rosa sp.	0	0	0	0	0	0	2	0	11	0	0	0	0	0	0	0	0	0	0	0	12	2	3	0	0	0	0	0
Taraxacum officinale	0	1	1	1	0	1	0	0	4	0	0	0	0	1	1	0	0	0	0	1	0	2	1	0	0	3	0	5
Tragopogon dubius	1	2	1	2	1	2	0	1	1	0	0	0	2	11	6	0	0	0	0	2	1	1	1	0	0	0	0	0
Vicia americana	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	8	1	0	0	0	0	0
Zigadenus venenosus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	3	0	2	2	0	1	0	0	0

a The full names and site characteristics of the treatment units are provided in Table 2.

APPENDIX 2 Correlation *(r)* among variables at 28 grassland treatment units in the Thompson Nicola region of British Columbia.

	Mechanical resistance 1.5 cm	Mechanical resistance 4.5 cm	Soil bulk density	Exposed mineral soil	Soil aggregate stability	Soil N	Soil C	Soil hydraulic conductivity	Soil A_h colour	Soil A_h thickness	Rough fescue cover	Bluebunch wheatgrass cover	Kentucky bluegrass cover	Litter cover	Microbiotic crust	Total plant biomass	Rough fescue biomass	Bluebunch biomass	Invasive species biomass	Forb biomass	Other grasses biomass	Litter biomass	Rough fescue density	Bluebunch density	Rough fescue seed heads	Bluebunch seed heads	Plant species richness
Mechanical resistance 1.5 cm	1.00																										
Mechanical resistance 4.5 cm	0.88	1.00																									
Soil bulk density	0.46	0.31	1.00																								
Exposed mineral soil	0.74	0.58	0.65	1.00																							
Soil aggregate stability	-0.62	-0.50	-0.66	-0.73	1.00																						
Soil N	-0.45	-0.27	-0.82	-0.67	0.73	1.00																					
Soil C	-0.44	-0.25	-0.83	-0.70	0.72	0.95	1.00																				
Soil hydraulic conductivity	0.30	0.26	-0.03	-0.03	0.17	0.14	0.21	1.00																			
Soil A_h colour	-0.20	-0.19	0.09	-0.09	0.09	0.08	0.00	0.27	1.00																		
Soil A_h thickness	-0.02	-0.19	-0.18	-0.18	-0.04	0.12	0.22	0.18	0.07	1.00																	
Rough fescue cover	-0.28	-0.31	-0.26	-0.27	0.32	0.20	0.24	0.37	0.34	-0.02	1.00																
Bluebunch wheatgrass cover	-0.02	-0.09	0.39	0.16	0.01	-0.13	-0.33	-0.18	0.04	-0.23	-0.26	1.00															
Kentucky bluegrass cover	-0.42	-0.31	-0.44	-0.41	0.35	0.48	0.48	-0.22	-0.07	0.20	-0.51	-0.08	1.00														
Litter cover	-0.75	-0.61	-0.56	-0.84	0.82	0.63	0.62	0.12	0.17	0.06	0.36	0.03	0.35	1.00													
Microbiotic crust	-0.14	-0.09	0.05	-0.16	-0.09	-0.10	-0.16	-0.36	-0.28	-0.07	-0.03	0.33	-0.21	-0.06	1.00												
Total plant biomass	-0.55	-0.56	-0.43	-0.33	0.50	0.32	0.42	0.09	0.21	0.18	0.54	-0.29	0.19	0.44	-0.12	1.00											
Rough fescue biomass	-0.29	-0.33	-0.29	-0.26	0.27	0.19	0.25	0.24	0.12	0.00	0.93	-0.36	-0.42	0.31	0.03	0.58	1.00										
Bluebunch biomass (kg ha^{-1})	0.19	0.12	0.37	0.46	-0.16	-0.17	-0.36	-0.09	0.35	-0.24	-0.20	0.64	-0.21	-0.21	-0.04	-0.30	-0.34	1.00									
Invasive species biomass	-0.02	-0.04	0.17	-0.05	0.23	0.05	-0.06	-0.24	-0.25	-0.13	-0.28	0.65	0.03	0.13	0.28	-0.30	-0.25	0.27	1.00								
Forb biomass	0.16	0.02	0.00	0.18	-0.08	-0.05	-0.14	0.26	0.08	0.19	-0.05	0.15	-0.08	-0.16	-0.03	0.00	-0.12	0.23	0.05	1.00							
Other grasses biomass	-0.28	-0.19	-0.16	-0.17	0.22	0.14	0.23	-0.26	-0.06	0.17	-0.51	-0.06	0.74	0.14	-0.12	0.34	-0.49	-0.20	-0.08	-0.21	1.00						
Litter biomass	-0.33	-0.45	-0.34	-0.22	0.36	0.21	0.34	0.20	0.03	0.30	0.61	-0.31	-0.16	0.34	-0.22	0.54	0.66	-0.16	-0.19	-0.04	-0.20	1.00					
Rough fescue density	-0.26	-0.29	-0.27	-0.26	0.26	0.21	0.20	0.29	0.21	-0.07	0.93	-0.22	-0.48	0.31	0.13	0.54	0.95	-0.24	-0.24	-0.02	-0.52	0.52	1.00				
Bluebunch density	0.16	0.00	0.25	0.28	-0.07	-0.01	-0.22	-0.24	0.24	-0.07	-0.31	0.62	0.17	-0.11	0.00	-0.19	-0.35	0.58	0.51	0.03	0.07	-0.34	-0.30	1.00			
Rough fescue seed heads	-0.10	-0.15	-0.13	-0.08	0.07	0.07	0.22	0.23	-0.01	0.28	0.32	-0.27	-0.10	0.12	-0.18	0.28	0.42	-0.07	-0.14	-0.02	-0.20	0.62	0.23	-0.23	1.00		
Bluebunch seed heads	0.24	0.12	0.42	0.62	-0.39	-0.44	-0.51	-0.41	-0.09	-0.28	-0.31	0.32	-0.20	-0.43	0.01	-0.21	-0.29	0.67	0.17	0.06	-0.05	-0.17	-0.30	0.39	-0.04	1.00	
Plant species richness	-0.30	-0.17	-0.21	-0.18	0.12	0.29	0.16	-0.37	-0.16	-0.19	-0.18	0.27	0.22	0.18	0.06	-0.08	-0.15	0.03	0.31	0.24	0.03	-0.25	-0.13	0.15	0.01	0.01	1.00